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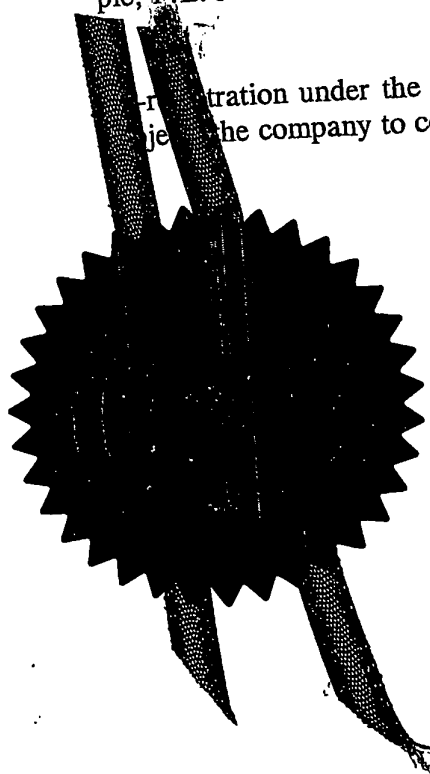
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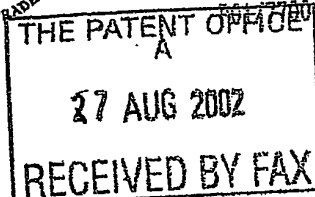
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1. Your reference

P32038-/GMM/PMC/MEA

2. Patent application number
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0219872.9

27 AUG 2002

3. Full name, address and postcode of the or of each applicant (underline all surnames)

The Queen's University of Belfast
University Road
Belfast
BT7 1NN
United Kingdom

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation

008891645001

4. Title of the invention

"Charged Particle Manipulation"

5. Name of your agent (if you have one)

Murgitroyd & Company

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

Scotland House
165-169 Scotland Street
Glasgow
G5 8PL

Patents ADP number (if you know it)

1198015

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Country

Priority application number
(if you know it)Date of filing
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7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application

Date of filing
(day / month / year)8. Is a statement of inventorship and of right to grant of a patent required in support of this request? (Answer 'Yes' if:
a) any applicant named in part 3 is not an inventor, or
b) there is an inventor who is not named as an applicant, or
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Description

29 ✓

Claim(s)

-

Abstract

-

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Priority documents

-

Translations of priority documents

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Statement of inventorship and right to grant of a patent (Patents Form 7/77)

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Request for preliminary examination and search (Patents Form 9/77)

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Request for substantive examination (Patents Form 10/77)

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11.

I/We request the grant of a patent on the basis of this application.

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Date

27 August 2002

Murgitroyd & Company

12. Name and daytime telephone number of person to contact in the United Kingdom

Peter McBride

0141 307 8400

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1 Charged Particle Manipulation

2
3 The present invention relates to the manipulation of
4 charged particles, in particular to methods and
5 apparatus for manipulating the phase space of at
6 least one charged particle.

7
8 Trapping of charged particles has a wide range of
9 potential applications including frequency
10 standards, quantum computation, quantum encryption
11 and material processing/fabrication.

12
13 However, there is a need for such applications to be
14 easier to realise.

15
16 According to a first aspect of the present invention
17 there is provided a method for manipulating the
18 phase space of at least one charged particle,
19 wherein a combination of alternating current and
20 direct current voltages applied to an electrode
21 forms a potential which provides a region of phase
22 space manipulation, and wherein the at least one

1 charged particle is situated to one side of the
2 electrode surface.

3
4 According to a second aspect of the present
5 invention, there is provided apparatus for
6 manipulating the phase space of at least one charged
7 particle, comprising at least one electrode arranged
8 on a surface and connected to a power supply capable
9 of applying both an alternating current voltage and
10 a direct current voltage so as to form a potential
11 which provides a region of phase space manipulation
12 to one side of the electrode surface.

13
14 Preferably, the apparatus further comprises pressure
15 control means to control the pressure of the space
16 surrounding the electrodes.

17
18 Preferably, the pressure control means comprises a
19 sealable chamber and gas pump means capable of
20 introducing and extracting gases from the chamber.

21
22 Preferably, the power supply is operable to vary the
23 alternating current and direct current voltages
24 applied.

25
26 Preferably, the power supply is operable to
27 individually alter the amplitude, waveform, and
28 frequency of the alternating current voltage, and is
29 operable to alter the magnitude of the direct
30 current voltage.

31
32 Preferably, the potential is an effective potential.

1 Preferably, the region of phase space manipulation
2 comprises a particle trapping region, wherein a
3 particle is constrained in a specific spatial area.

4
5 Preferably, the region of phase space manipulation
6 comprises a particle guide region, wherein a
7 particle's motion is restrained by at least one
8 degree of freedom.

9
10 Preferably, a plurality of electrodes are provided.

11
12 Preferably, the electrodes are arranged in an array
13 such that the at least one particle is situated to
14 one side of the array.

15
16 Preferably, the array is substantially planar.

17
18 Alternatively, the array is hemispherical.

19
20 According to a first embodiment of the present
21 invention, a single electrode is provided, and is
22 surrounded by a plane held at a constant potential.

23
24 Preferably, the electrode is circular.

25
26 Preferably, the plane is earthed.

27
28 Preferably, the frequency of alternating current
29 voltage applied to the circular electrode is of a
30 frequency having a period that is less than the time
31 taken for light to pass over the diameter of the
32 circular electrode.

1 According to a second embodiment of the present
2 invention, the voltages applied to adjacent first
3 and second sets of electrodes in a planar array can
4 be varied such that the at least one particle can be
5 moved from the particle trapping region provided by
6 the first set of electrodes to the particle trapping
7 region provided by the second set of electrodes.

8
9 Each set of electrodes may consist of one electrode,
10 or of a plurality of electrodes.

11
12 Preferably, at least one particle is moved from a
13 first trapping region provided by a first set of
14 electrodes to a second trapping region provided by a
15 second set of electrodes, wherein the voltages
16 applied to the sets of electrodes is changed from an
17 initial, to an intermediate and then to a final
18 configuration, and wherein;

19 in an initial configuration, a first set of
20 electrodes is biased to a holding voltage to form a
21 first particle trapping region to trap at least one
22 particle therein, and an adjacent second set of
23 electrodes is biased to zero volts;

24 in an intermediate configuration, both sets of
25 electrodes are biased to the holding voltage to form
26 a merged particle trapping region that traps the at
27 least one particle;

28 in a final configuration, the first set of
29 electrodes is biased to zero volts, and the second
30 set of electrodes is biased to the holding voltage
31 to form a second particle trapping region, that
32 traps the at least one particle.

1 Preferably, the process of moving at least one
2 particle from a first trapping region provided by a
3 first set of electrodes to a second trapping region
4 provided by a second set of electrodes is repeatable
5 to move the at least one particle along a chosen
6 path on the planar array.

7
8 The planar array can be formed using printed circuit
9 board, lithographic, or focussed ion beam
10 technology.

11
12 According to a third embodiment of the present
13 invention, a series of electrodes are provided, the
14 voltages applied to which are controllable such that
15 the at least one particle can be moved from a first
16 particle trapping region to a second particle
17 trapping region, wherein the first trapping region
18 is larger than the second trapping region.

19
20 Preferably, the voltages applied to the electrodes
21 are controllable such that the at least one particle
22 can be moved between a plurality of successively
23 smaller trapping regions.

24
25 Preferably, the series of electrodes comprises a
26 plurality of concentrically arranged circular
27 electrodes.

28
29 Preferably, in an initial state, every electrode has
30 a combination of alternating current and direct
31 current voltages applied such that at least one
32 particle is trapped in a first trapping region;

1 the voltage applied to the outer electrode is
2 changed such that, in an intermediate state, the at
3 least one particle is trapped in a first
4 intermediate trapping region provided by the
5 remaining inner electrodes; and

6 the voltage applied to the electrode adjacent
7 to the outer electrode is changed such that in a
8 final state, the at least one particle is trapped in
9 a second trapping region provided by the innermost
10 electrode.

11
12 Preferably, in the transitions from the initial to
13 intermediate and the intermediate to final states,
14 the outer and adjacent electrodes respectively are
15 set to zero volts.

16
17 Preferably, a plurality of electrodes each provide a
18 further intermediate trapping region, such that,
19 between the initial state and the final state, the
20 at least one particle passes through a plurality of
21 intermediate states, being trapped in successively
22 smaller intermediate trapping regions.

23
24 Preferably, in an initial state, an outermost
25 electrode has a first combination of alternating
26 current and direct current voltages applied, and a
27 background voltage is applied to the remaining
28 electrodes such that, in an initial state, at least
29 one particle is trapped in a first trapping region;
30 the electrode adjacent to the outer electrode
31 is set to the first combination of voltages and the
32 background voltage is applied to the outer electrode

1 such that, in an intermediate state, the at least
2 one particle is trapped in a first intermediate
3 trapping region; and

4 the innermost electrode is set to the first
5 combination of voltages and the background voltage
6 is applied to the adjacent electrode such that, in a
7 final state, the at least one particle is trapped in
8 a second trapping region.

9
10 Preferably, the background voltage is zero volts.

11
12 Preferably, a plurality of electrodes is provided
13 such that, between the initial state and the final
14 state, the at least one particle passes through a
15 plurality of intermediate states, being trapped in
16 successively smaller intermediate trapping regions.

17
18 Preferably, the innermost electrode is provided with
19 an aperture; and

20 when the at least one particle is in the final
21 state, a voltage is applied to the aperture such
22 that the at least one particle is urged through the
23 aperture.

24
25 Preferably, each side of the aperture is
26 differentially pumped so that a gas passing through
27 the aperture undergoes a supersonic expansion, so as
28 to cool the particles that are urged through the
29 aperture.

30
31 According to a fourth embodiment of the present
32 invention, the voltages applied to an electrode are

1 such that one type of charged particle can be
2 distinguished from another.

3

4 Preferably, different types of charged particle are
5 trapped at different distances perpendicularly from
6 the surface of the electrode.

7

8 Preferably, the distance is dependent on the charge
9 and/or mass of the charged particle.

10

11 Preferably, a first type of charged particle is
12 trapped at a first perpendicular distance from the
13 electrode, and a second type of charged particle is
14 trapped at a second perpendicular distance from the
15 electrode, wherein the mass of the first charged
16 particle is greater than the mass of the second
17 charged particle, and the second perpendicular
18 distance is greater than the first perpendicular
19 distance.

20

21 Preferably, at least one particle trapped at the
22 second perpendicular distance is subject to the
23 potential formed by a voltage sequence applied to a
24 second set of electrodes.

25

26 Preferably, the voltage sequence applied to the
27 second set of electrodes is such as to transport
28 said at least one particle from one trapping region
29 to another along a predetermined path.

30

1 Preferably, the dimensions of the second set of
2 electrodes are of a much larger scale than the
3 dimensions of the trap electrode.

4
5 Preferably, an aperture is provided on an electrode
6 such that the type of particle that is closest to
7 the surface of the electrode can pass through the
8 aperture.

9
10 Preferably, each side of the aperture is
11 differentially pumped so that a gas passing through
12 the aperture undergoes a supersonic expansion, so as
13 to cool the particles that are urged through the
14 aperture.

15
16 According to a fifth embodiment of the present
17 invention, the voltages applied to an electrode can
18 be changed such that a trapped particle moves in a
19 direction perpendicular to the plane of the
20 electrode.

21
22 Preferably, at least one trapped particle can be
23 lowered to a region where it will interact with at
24 least one other particle; and
25 the particles that result from the interaction
26 can then be raised up again, together with particles
27 that have not interacted.

28
29 Preferably, the electrode is formed with an aperture
30 and the applied voltage can be changed to bring a
31 particle close to the aperture; and

1 a voltage is applied to the aperture such that
2 the particle is urged through the aperture.

3
4 Preferably, each side of the aperture is
5 differentially pumped so that a gas passing through
6 the aperture undergoes a supersonic expansion, so as
7 to cool the particles that are urged through the
8 aperture.

9
10 According to a sixth embodiment of the present
11 invention, an array of electrodes is provided, the
12 voltages applied to which trap a first type of
13 particle which can interact with a second type of
14 particle, to form a reactant particle which falls to
15 the bottom of a trap and is swept away through an
16 extraction hole.

17
18 According to a further aspect of the present
19 invention, there is provided apparatus for carrying
20 out the method of the sixth embodiment, comprising
21 an array of electrodes arranged on a surface, at
22 least one of which is connected to at least one
23 power supply capable of applying both an alternating
24 current voltage and a direct current voltage,
25 wherein a region of phase space manipulation is
26 provided to one side of the electrode surface.

27
28 Preferably, the array of electrodes further
29 comprises at least one aperture for the extraction
30 of trapped particles.

31
32 Preferably, each electrode comprises one aperture.

11

1 Preferably, the reactant particle is accelerated
2 through a potential and detected so that the
3 position of the original first type of particle can
4 be detected.

5
6 The present invention will now be described, by way
7 of example only, with reference to the accompanying
8 drawings, in which:

9
10 Fig. 1 illustrates potential contours suitable for
11 trapping a charged particle formed by an electrode
12 in accordance with a first embodiment of the
13 invention;

14
15 Fig. 2 illustrates a third embodiment of the
16 invention;

17
18 Fig. 3 illustrates potential contours where a
19 particle will not be trapped;

20
21 Fig. 4 illustrates a fourth embodiment of the
22 present invention;

23
24 Fig. 5 illustrates apparatus used in accordance with
25 all embodiments of the invention; and

26
27 Fig. 6 illustrates a sixth embodiment of the
28 invention.

29
30 In the adiabatic approximation, a particle of mass m
31 and charge q subject to a set of DC and rapidly
32 varying AC voltages (angular frequency Ω) applied

1 to a series of electrodes moves as if subject to an
2 effective potential V^* which is a linear combination
3 of an AC term and a DC term, and takes the form

$$4 \quad V^*(R_0) = q^2 E_0^2 / 4m\Omega^2 + q\Phi, \quad (1)$$

5 where E_0 is the E-field due to the AC voltages, Φ , is
6 the electrostatic potential due to the DC voltages
7 and R_0 is the position of an ion averaged over
8 several cycles of the AC voltage.

9
10 With respect to an electrode, the AC part is always
11 repulsive whereas the DC part can be either
12 attractive or repulsive.

13
14 A DC system alone cannot trap ions since the
15 potential has a negative curvature in at least one
16 direction. However, the combination of AC and DC
17 voltages results in an effective potential that at
18 some locations has a positive curvature in all
19 directions such that charged particles can be
20 trapped.

21
22 Equation (1) above can be re-cast as

$$23 \quad V^*(R_0) = qV_{dc}(kE_0^2 + \Phi_r) \quad (2)$$

24
25
26 where a factor of q has been dropped through
27 conversion to electron-volts for the units of
28 potential and by considering singly charged ions
29 (although the system described here is not subject
30 to that limitation). k has the value

31

$$k = q\gamma^2 / 4m\Omega^2 \quad (3)$$

1

2

3

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31

where γ is a scaling parameter for the AC voltages applied to the system of electrodes, compared to the DC voltage applied, defined explicitly by $\gamma = V_{ac}/(V_{dc}l)$, where V_{ac} and V_{dc} are the actual voltages applied to the electrodes and l gives the length-scale associated with the whole design.

The variable k thus serves as a parameter which can illustrate the scaling of a potential. For a specific trapped particle, γ or Ω can be varied. The variables q and m are specific to the particle that is trapped.

Thus, in contrast to known particle trapping or guiding techniques, the present invention provides for the trapping or guiding of particles where the trapping electrodes do not have to surround the particle. The electrodes can be arranged in any suitable formation. One option would be for them to lie in a plane. Other options are possible; in particular, the electrodes may be in an array which is substantially planar, but in which some are at relatively raised or lowered positions. The electrodes may also be arranged, for example, in a hemispherical, ellipsoidal or paraboloid configuration.

In a first embodiment, a spot trap is provided. A single electrode is surrounded by a large earth

1 plane. The system is readily scalable through
2 appropriate scaling of the value of k .

3
4 Provided the AC voltage is applied at a frequency
5 sufficiently low to ensure light can travel across
6 the system in a time much less than one period, the
7 potential due to the AC voltage is simply that due
8 to the DC voltage but modulated in time.

9
10 Fig. 1 is a plot of the potential contours for a
11 specific trapping configuration of a circular
12 electrode. In this system, a $10\mu\text{m}$ radius spot was
13 chosen and had a DC voltage of -1V applied to it
14 with respect to the earth plane. The value of the
15 scaling parameter k was chosen to be 100.

16
17 The horizontal ordinate is the perpendicular
18 distance from the electrode plane and the vertical
19 ordinate the radial distance from the symmetry axis,
20 both in μm . The minimum of the effective potential
21 (located at approximately $r=0\mu\text{m}, z=11\mu\text{m}$) has a value
22 of -0.186V with respect to the surrounding earth
23 plane. Contours are shown for -0.18 to -0.11V in
24 0.01V intervals.

25
26 Because the system concerned has cylindrical
27 symmetry about an axis passing through the centre of
28 the circular electrode and perpendicular to the
29 plane it is sufficient to demonstrate the resultant
30 effective potential has the form required to trap
31 particles in one plane passing through the symmetry
32 axis to demonstrate the system is an ion trap. It

15

1 can therefore be seen that this is a trapping
2 configuration.

3
4 Numerical tests have shown that the system traps
5 ions for a range of values of k greater than about
6 80.

7
8 The distance of the trap centre from the surface and
9 the curvature at the bottom of the trap can be
10 changed by changing the value of k . In particular,
11 as the value of k is increased, particles of a given
12 mass will be trapped at a point more distant from
13 the plane of the electrode. As k is dependent on a
14 particle's mass, it follows that, for a given value
15 of k , particles of heavier mass will lie closer to
16 the plane of the electrode. Furthermore, as k
17 increases, the curvature of the bottom of the
18 potential well changes, resulting in a larger sized
19 and differently shaped trapping region. Note that
20 this change in the trapping region is distinct from
21 the change in trapping region brought about by
22 funnelling techniques disclosed below, where the
23 shape of the trapping region remains constant.

24
25 The ion will remain trapped in the trapping region
26 provided the adiabaticity parameter is small enough.

27
28 It is given by

$$\eta = \frac{2q|\nabla E_0|}{m\Omega^2} \quad (4)$$

29

30

1 Experiments have shown that this parameter must have
2 a value of less than 0.3 for stable trapping. Tests
3 indicate this parameter will have a value of about
4 0.05 near the minimum of the effective potential so
5 the trapping is expected to be stable. Further
6 numerical tests can be made to verify this assertion
7 and to determine the volume over which stable
8 trapping occurs.

9
10 This principle is not restricted to a simple
11 circular trapping electrode. For example, a matrix
12 of electrodes could be fabricated. The voltages
13 applied to the various electrodes can then be chosen
14 to manipulate particles in a number of ways, some of
15 which are illustrated below.

16
17 For example, in a second embodiment, the voltages
18 applied to the various electrodes in an array could
19 be chosen for example so that all of those lying
20 inside a given region are biased with an appropriate
21 DC voltage and an AC voltage with the remaining
22 electrodes being biased to zero volts. Gradually
23 changing the location of the region inside which the
24 biased electrodes reside (i.e. changing electrodes
25 successively from being biased to being at earth and
26 the other way in a systematic fashion) corresponds
27 to moving the trap location across the surface,
28 effectively creating a particle conveyor belt.
29 In a third embodiment, the electrodes can act as a
30 funnel, the voltages being varied so as to bring
31 trapped particles from a wide area to be
32 concentrated in a central region.

1 An example of an electrode configuration that can
2 act as a funnel is shown in Fig. 2. A series of
3 concentric electrodes 10 is provided, which
4 initially all have the same AC and DC voltages
5 applied. They are surrounded by a large earth plane
6 12. Thus, in an initial state, the system looks
7 like a spot-trap, with a diameter equal to D_1 , and k
8 set to a particular value. After some time in this
9 configuration, the outer electrode would be set to
10 0V (making it seem like part of the earth plane),
11 whilst the waveform applied to the others would be
12 changed to keep k at the same predetermined value
13 (note 1 has changed because the diameter of the spot
14 is equal D_2). There is then a first intermediate
15 state, where the effective potential now has the
16 same form, but is slightly shrunk in comparison to
17 the potential in the initial state. Thereafter,
18 successive electrodes are grounded from the outside
19 in, always keeping k constant, until a final state
20 is reached where the particle is trapped by the
21 central electrode.

22
23 An alternative way of funnelling a particle may be
24 to provide the same electrode structure, but
25 initially only have the outer few rings with
26 voltages applied, with those inside being earthed.
27 Then, moving successively from the outside, each
28 electrode is set to zero while one more inner has
29 voltages applied. Thus, the particles are again
30 focussed in a central region.
31

1 The innermost electrode can be provided with an
2 aperture, which acts as an extraction hole. As seen
3 above, for smaller values of k , the particles are
4 trapped closer to the surface of the electrodes. As
5 k is reduced further, the potential ceases to act as
6 a trapping potential. At a certain value of k ,
7 (found to be 77.7 for the specific spot trap
8 mentioned above), the trap "breaks" and a trapped
9 particle can escape. The potential contours at this
10 point are illustrated in Fig. 3. A biased
11 extraction electrode can optionally be provided on
12 the other side of the aperture.

13
14 When the system is used with a buffer gas, the two
15 sides of the extraction region can be differentially
16 pumped so that the buffer gas going through the
17 aperture undergoes a supersonic expansion so that
18 the beam of particles passing through the aperture
19 is cooled.

20
21 In a fourth embodiment, the abovementioned spot trap
22 and conveyor belt configurations can be combined to
23 provide manipulation of particles, where particles
24 of differing mass or charge can be separated and
25 treated differently.

26
27 The scaling parameter, k , is inversely proportional
28 to the mass of the trapped particles, so that more
29 massive particles are trapped closer to the surface
30 of an electrode. Fig. 4 shows a configuration where
31 a series of conveyor electrodes 14 is provided,
32 forming a conveyor 16, to which the voltages applied

19

1 allows the conveyor 16 to transport particles from
2 one trapping region to another. A spot trap
3 electrode structure 18 is situated in the middle of
4 the conveyor 16.

5
6 The relative length scales of the conveyor
7 electrodes 14 and the spot trap electrodes 18 are
8 such that the conveyor electrodes 14 are much larger
9 than the spot trap electrodes 18. When a relatively
10 light particle is trapped by the spot trap 18, it is
11 trapped at such a height that, due to the local
12 nature of the e-field and potential, it is more
13 influenced by the potential of the conveyor 16 than
14 the spot trap 18.

15
16 Hence, one can envisage a system where (possibly
17 after some interaction) particles arrange themselves
18 at different distances from the surface depending on
19 their masses. The less massive particles would then
20 rise up and be swept away by a conveyor belt, with
21 the heavier particles remaining in the trap region.

22
23 After such a process, the remaining heavier
24 particles could be passed through an extraction
25 hole, using the methods described above.

26
27 Alternatively, one might be interested in a process
28 where the particle mass increases. In this case the
29 trap could initially be programmed to hold both the
30 mass before and after an interaction. It then could
31 be periodically programmed to have a lower value of
32 k so the lighter (unchanged) particles rise up to be

1 transported to a holding zone. The trap could then
2 become part of a conveyor belt, perpendicular to the
3 direction the lighter particles were moved. The
4 heavier (changed) particles would then be
5 transported away for further processing after which
6 the lighter particles could be returned (possibly
7 with others added) to the interaction region.

8
9 In a fifth embodiment, where particles are trapped
10 at a certain height, the value of the scaling
11 parameter k can be decreased such that the particles
12 are lowered towards the electrode surface to
13 interact with other particles deposited there. The
14 value of k can then be increased again so that the
15 product particles, and any unchanged particles can
16 be raised up.

17
18 In all of the above embodiments, printed circuit
19 board technology can be used to construct the
20 electrode arrays. The proximity of adjacent
21 electrodes is limited by cross talk effect, but the
22 nature of the interactions should be such that
23 useful devices can be constructed for the
24 transportation of various particles, such as, for
25 example, ions or electrons.

26
27 Indeed, there are many technologies for forming such
28 arrays, such as focussed ion beam or lithographic
29 techniques. The choice of construction method will
30 depend on the length scale and application of the
31 particular array to be constructed.

32

1 The above concepts have a wide range of potential
2 applications. In particular, the techniques above
3 may be used to enable miniaturisation and
4 parallelisation of current techniques for frequency
5 standards, quantum computation, quantum encryption
6 and material analysis.

7
8 In addition, the techniques are directly applicable
9 to the manufacture of devices for manipulating ions,
10 for use in high end biomolecular experiments.

11
12 It will be appreciated that the electrodes of an
13 apparatus, which are connected to an appropriate
14 power supply, will normally be contained within a
15 sealable chamber, and a gas pump is provided to
16 introduce and extract gas in order to vary the
17 pressure and control the quality of vacuum provided
18 in the chamber.

19
20 Fig. 5 shows an apparatus that uses the techniques
21 of the present invention, which is particularly
22 intended to be used with biomolecular ions.

23
24 Ions 20 are introduced into a chamber 24. Optional
25 gate electrodes 22 are used to control the
26 introduction of the ions 20. The ions 20 are used
27 to seed an array of trap electrodes 26.

28
29 A pump and gas inlet valve (not shown) control the
30 introduction and extraction of a background buffer
31 gas, to control the vacuum provided by the chamber
32 24.

1 The voltages applied to the array 26 can be varied
2 to manipulate ions 20, as described above. At any
3 time, the trapping voltages can be switched off and
4 an extraction voltage can be applied to an
5 extraction plate 28 to accelerate the ions 20
6 through a flight tube 30 towards a position-
7 sensitive detector 32. Although the ions 20 may
8 undergo several collisions in the flight tube 30
9 these collisions will be brief and with the much
10 lighter buffer gas partners. Accordingly these
11 collisions should not destroy the positional or
12 time-of-flight information.

13
14 Time-of flight will be used to distinguish genuinely
15 trapped or guided ions 20 from background ions so
16 the time-gated image on the position-sensitive
17 detector 32 corresponds to a snap-shot of the ion 20
18 locations just prior to the application of the
19 extraction voltage.

20
21 It will be appreciated that trapped ions have a
22 thermal energy distribution that means they will
23 have a finite chance of escaping, much as a water
24 molecule has a chance of evaporating from a liquid
25 below the boiling point. When such a trapped
26 particle escapes, it passes through the aperture.
27 However, as the voltages are varied, this shall
28 occur slightly before the normally expected
29 transmission time of that particular particle. The
30 times when a particle may escape outside of these
31 transmission times will depend on the values and
32 rate of changes of the amplitude, waveform, and

1 frequency of the voltages applied. Thus, the mass
2 of the particle can be determined by correlating the
3 time of passage through the aperture with the state
4 of the trap at that time.

5
6 Various buffer gas collision regimes can be
7 explored, particularly the high collision frequency
8 limit (useful for material processing and working
9 with Biomolecules) and the collisionless limit
10 (useful for quantum computation and encryption). In
11 the high frequency limit the ions will rapidly
12 become thermalised through collisions with
13 background gas and one another. This background can
14 be a rare gas buffer so no unwanted chemical
15 reactions occur, or it could be, for example, water
16 to investigate hydration of biomolecules. A rare
17 gas buffer can easily be cooled to liquid N₂
18 temperature when the characteristic energy
19 associated with each degree of freedom will be about
20 3meV so the trapped ions will lie inside the
21 trapping region, which is seen as the innermost
22 contour of Fig. 1.

23
24 The details of the dynamics in the collisionless
25 limit are harder to calculate although this can be
26 done using certain computer simulation techniques.

27
28 For a given voltage configuration the motion of a
29 single ion can be approximated by a superposition of
30 harmonic motions, which may be coupled.

31

1 Another device that can be constructed using the
2 principles of the invention is a single
3 reconfigurable trap. This can be a few centimetres
4 across, with circular electrodes centred about an
5 extraction region consisting of a small aperture
6 with the trap system to one side and a biased
7 extraction electrode to the other side. For such a
8 trap, the effective potential takes the form shown
9 in Fig. 1. The effective potential contours are
10 chosen so that the innermost contour corresponds to
11 room temperature, compared to the minimum.

12
13 The trap will be gradually reconfigured so that the
14 length scale gradually reduces from about 3cm to
15 50 μ m, so all of the ions trapped in the potential
16 are gathered into a successively smaller volume,
17 similar to a deflating balloon.

18
19 The trapping nature will then be changed so that the
20 ions are free to move towards the extraction region,
21 centred at the origin. The potential will take the
22 form shown in Fig. 3 (note change in z-axis), when
23 the trapped ions will escape through the extraction
24 region. The two sides of the extraction region can
25 be differentially pumped so the buffer gas going
26 through the aperture will undergo a supersonic
27 expansion giving further cooling to the beam of
28 biomolecular ions.

29
30 The resultant pulsed source of cold biomolecular
31 ions will be ideal for investigating their reactive

1 scattering behaviour, hence creating a new and
2 topical research field.

3
4 The principles of the present invention can also be
5 used to construct a position-sensitive detector,
6 which is illustrated in Fig. 6.

7
8 An array of traps 34 forms a planar electrode
9 structure 36 and is loaded with a specific molecular
10 ion (A^+) chosen to be able to react associatively
11 with a particular biomolecule or class of
12 biomolecules (B). The choice of A^+ relates to the
13 specificity of the detector. A microchannel plate
14 40 is provided, the front surface of which is biased
15 highly negatively to attract the positive ions.
16 Alternatively, any suitable position sensitive
17 charged particle detector may be used in place of a
18 microchannel plate.

19
20 When a molecule B approaches the planar structure 36
21 it can then react with one of the sensor molecule
22 ions in the associative reaction:



23
24
25
26 The trap configuration is arranged so that the
27 product ion, being more massive falls towards the
28 electrode surface 36 eventually being swept through
29 due to a field penetrating through one of an array
30 of small holes 38. This penetrating field occurs as
31 a natural consequence of biasing the front surface
32 of the microchannel plates 40 highly negative. Note

1 that the same effect could be achieved by having the
2 back face of the electrode array being negatively
3 charged. The ion is then accelerated from the hole
4 38 towards a microchannel plate 40, which will be
5 the front-end of a traditional position sensitive
6 detector (something akin to an image intensifier).
7 The resultant detection event provides a record of
8 the position of the biomolecule prior to the
9 interaction.

10
11 It may additionally be possible to cycle the
12 trapping so that the more massive product ions are
13 held in the trap and can only reach the penetrating
14 field periodically. In this case, time-of-flight
15 information can be used to determine the mass of the
16 product ion and hence determine the mass of A^+ as
17 well as the class of molecules to which it belongs.

18
19 The innate capability of the trapping array to store
20 different ions at different locations could be
21 exploited to store different species A^+ at different
22 locations, making the system able to distinguish a
23 range of biomolecules (B) simultaneously.

24
25 A bespoke CAD/simulation package can also be
26 provided to aid in the design of arrays to trap or
27 guide charged particles. For a given trap
28 configuration subject to any sequence of applied
29 voltages, the motion of trapped ions can in
30 principle be solved exactly through solution of
31 Maxwell's equations for the fields and Newton's
32 equations for the motion of the ions. However, this

27

1 might be computationally intractable for the scale
2 of problems envisaged.

3
4 Because of the length and frequency scales involved,
5 linear combinations of solutions of Laplace's
6 equation can be used in place of the full solution
7 of Maxwell's equations. This problem is
8 computationally tractable for arbitrary geometries
9 and, due to the near-symmetries of the trap arrays
10 proposed, amenable to further speed-ups through
11 multi-resolution analysis. Using solutions of
12 Laplace's equation obtained in this manner, the
13 properties of the trapping or guiding arrays will be
14 deduced by solving the dynamics of the trapped ions
15 at various levels of approximation ranging from full
16 explicit solution of the motion of trapped ions
17 coupled to a Monte-Carlo simulation for collisions
18 with the buffer gas (computationally expensive) to
19 simply calculating the effective trapping potential
20 averaged over a particular 'trapping sequence' of
21 applied voltages and then using statistical
22 distributions and friction models for the ions
23 subject to this effective potential (computationally
24 cheap).

25
26 Such simulations will first be used to assess the
27 range of validity of computationally cheap
28 strategies. Once this is established, the effective
29 potential and adiabaticity parameter for various
30 trap/guide configurations and 'trapping sequences'
31 will be used to predict their behaviour.
32

1 Control of the program will be achieved through a
2 visual interface, leading to a bespoke
3 CAD/simulation program for ion trap/guide arrays,
4 which can be made available to researchers in the
5 field, and can act over an array of PC's acting as a
6 parallel computer. Both the solution of Laplace's
7 equation and the calculation of trajectories are
8 amenable to parallel computation.

9
10 Various modifications can be made without departing
11 from the scope of the present invention. In
12 particular, the charged particles may comprise ions,
13 electrons, or any other suitable charged particles.

14
15 The fabrication of the electrode arrays may be by
16 any suitable means, of which printed circuit board
17 technology, lithographic methods, and focussed ion
18 beam methods are examples only.

19
20 The shape of electrodes in each embodiment may take
21 any suitable shape, and the examples given should
22 not be taken as limiting these to any particular
23 shape. For example, a funnel configuration could be
24 implemented by means of a series of concentric
25 circular electrodes. These electrodes could be
26 ellipsoidal, square, or any other suitable shape.

27
28 The voltages applied to the electrodes may take any
29 suitable form, and can be modulated before being
30 sent to the electrodes. For example, the voltages
31 could be square waves to enable digital logic
32 techniques to be used when processing the

1 information. Furthermore, the voltages applied to
2 the electrodes can be of appropriate polarity to
3 attract or repel specific particles. For example,
4 in the apparatus for carrying out the method of the
5 sixth embodiment, the microchannel plate is biased
6 negatively. However, it could be charged positively
7 to attract negative particles.

8
9 It will also be acknowledged that in configurations
10 such as the conveyor belt, their operation is
11 described in terms of actually transporting
12 particles; however the voltage sequences can be
13 applied even when no particles are present, so that
14 the conveyor configuration may be always active, to
15 transport particles as and when they are present.

16
17 It will also be appreciated that specific
18 applications of the principles of the invention may
19 be applied in combination.

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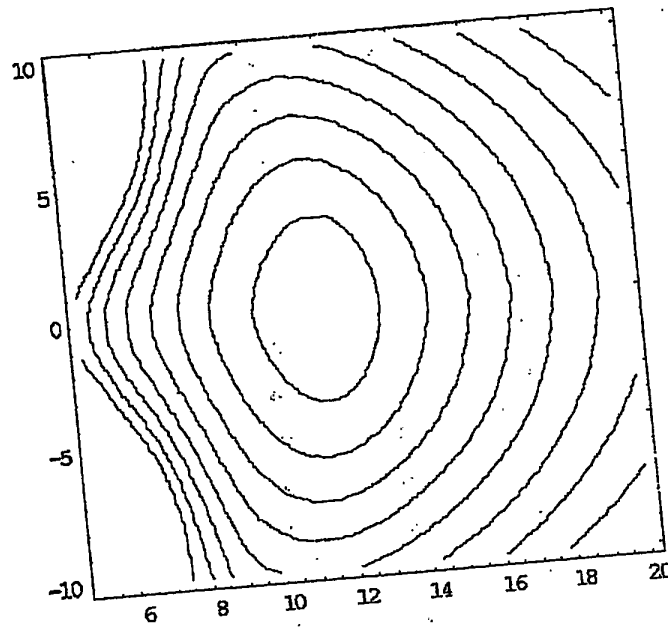


Figure 1

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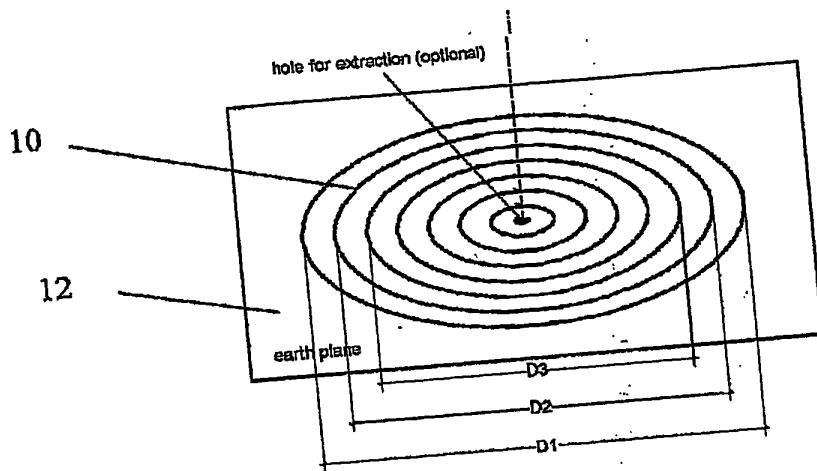


Figure 2

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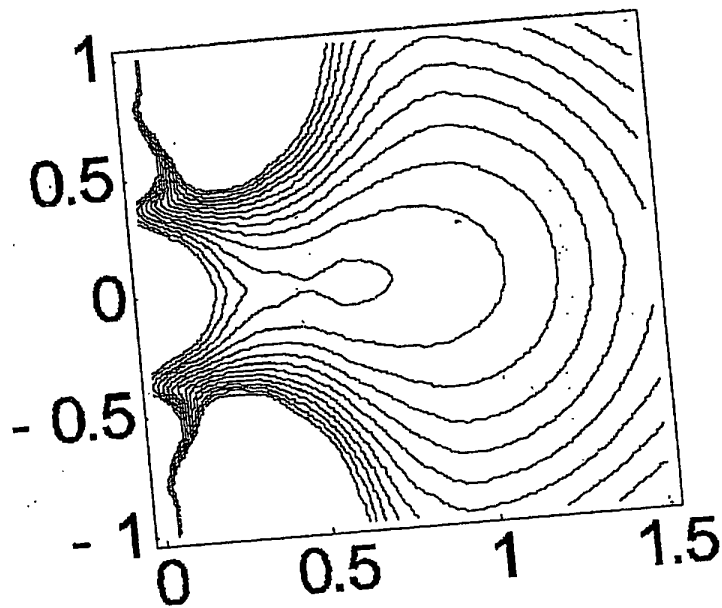


Figure 3

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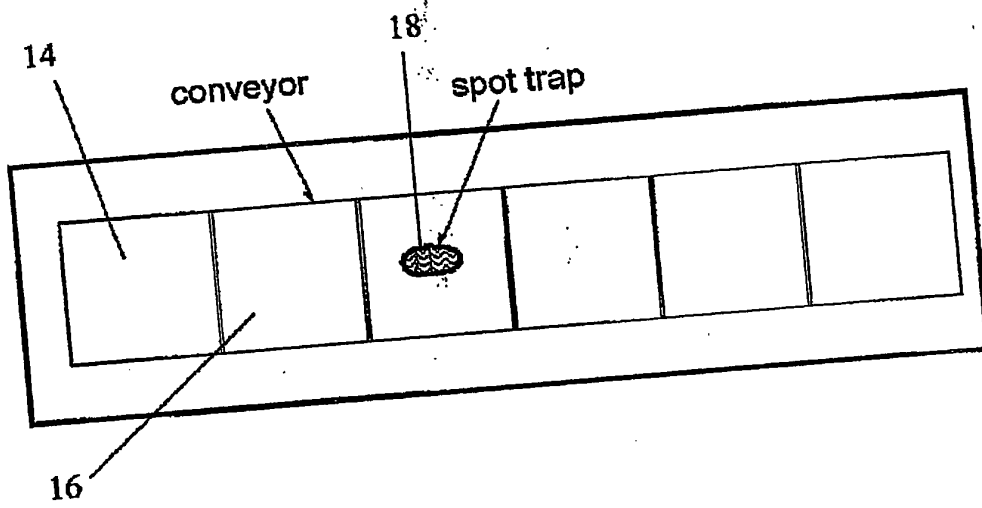


Figure 4

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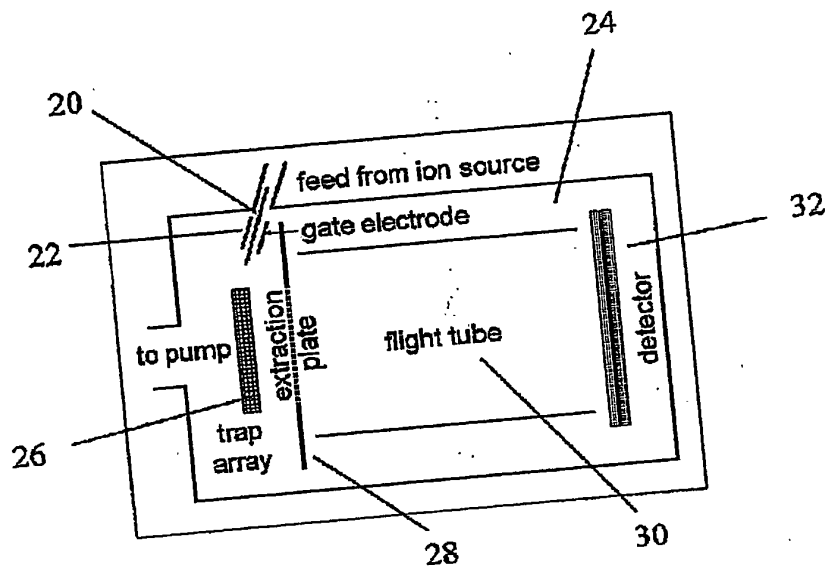


Figure 5

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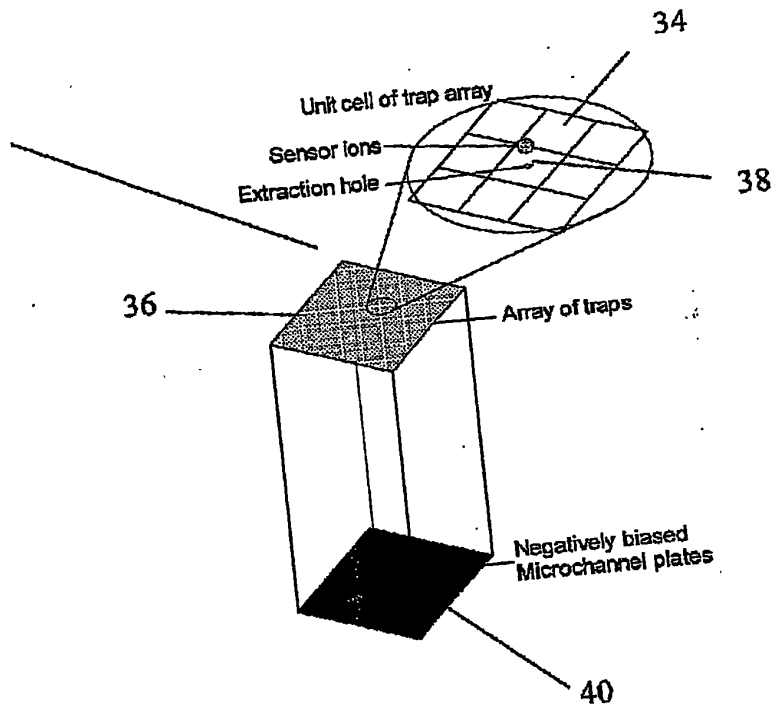


Figure 6



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